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COOPERATIVE MODULATION TECHNIQUES FOR LONG HAUL RELAY IN SENSOR NETWORKS

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Abstract— **Cooperative modulation techniques can reduce the energy requirements for the long haul transmission of data from localized sensor networks. This savings is vital in extending the battery life of power limited sensor nodes communicating over a time-limited channel. Several transmission methods, including a novel scheme that conveys information via node selection, are analyzed. The energy cost in local communications needed to support the cooperative long haul link is determined and used to make comparisons between the techniques.**

I. Introduction

There are many scenarios in remote sensing applications, such as environmental monitoring, planetary exploration, and reconnaisance, in which a number of geographically local elements must individually communicate with a much more distant resource, such as an orbiting satellite, to relay the sensed information. Examples range from sensor networks used to measure local weather, seismic, or aquatic activity, to a collection of rovers examining a boulder field for elemental analysis. Due to the distance-squared wave propagation loss, communication between the surface and an orbiting satellite requires orders of magnitude more power than does communication between local surface units. By sharing the information to be transmitted to the satellite between the surface units and then using a cooperative modulation scheme that is distributed among the nodes, the total energy necessary to transmit the data from the surface to orbit can be reduced, extending the lifetime of the energy-limited surface units. In order to demonstrate the possible gains of cooperative modulation, a comparison between the standard technique of each node separately transmitting its data to the satellite and several cooperative techniques where information is shared locally and then jointly transmitted to the satellite is made.

Consider the following situation. A set of N surface units are clustered on the planet such that they all simultaneously fall within the footprint pattern of an orbiting satellite. Each surface unit has a set of D information bits that must be reliably transmitted to the satellite during a window of visibility lasting T_v seconds. Assume we have a fixed energy-per-bit available for transmission. Each of the different cooperative techniques will divide this energy and transmit it to the orbiting receiver, where a decision on the transmitted information will be made. As the choice of whether to use coherent or non-coherent detection is one of hardware complexity rather than performance, we will first present comparisons of the cooperative techniques using binary phase- shift keying (BPSK) with ideal carrier phase tracking, followed by comparisons using non-coherent binary frequency-shift keying (BFSK).

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II. Communication Methods

A. Non-Cooperative on Orthogonal Channels (NCOC)

Before examining the cooperative techniques, we analyze the performance of a standard communication scheme that does not assume any cooperation between the nodes. This will provide us with a performance baseline with which to compare the cooperative techniques.

In this scheme, each of the N sensor nodes transmits its D data bits separately to the orbiter on an orthogonal channel (time, frequency, or code). For example, consider the case where each node is assigned a unique frequency band. The n^{th} node will encode its D data bits, $\{d_{n,0}\cdots d_{n,D-1}\}$, at a rate $1/NT$ into a BPSK signal

$$s_n(t) = \sum_{k=0}^{D-1} \sqrt{\frac{2E_b}{NT}} d_{n,k} p_{NT}(t) \cos(\omega_n t),$$

where E_b is the received energy-per-bit and $p_{NT}(t)$ is a rectangular pulse of duration NT. This signal is transmitted and subsequently received along with those of the other nodes at the orbiter, each with a separate delay of τ_n. Modeling the receiver front end noise as an additive Gaussian noise process, $n(t)$, with a flat power spectral density of $N_o/2$, we write the received signal as

$$r(t) = \sum_{n=0}^{N-1} \sum_{k=0}^{D-1} \sqrt{\frac{2E_b}{NT}} d_{n,k} p_{NT}(t-\tau_n) \cos(\omega_n t + \theta_n) + n(t),$$

where $\{\theta_n = \omega_n \tau_n\}$ are modeled as independent uniform random phase offsets. Assuming perfect carrier frequency and phase estimation as well as bit synchronization for each of the N channels, an N channel coherent detector is used, resulting in a probability of bit error of $P_e = \Phi\left(-\sqrt{\frac{2E_b}{N_o}}\right)$, where $\Phi(\cdot)$ is the cumulative distribution function of the zero-mean, unit-variance Gaussian density.

For the corresponding non-coherent system, each of the N nodes again transmits its D data bits separately to the orbiter on a unique frequency channel, with the n^{th} node now encoding its D data bits at a rate $1/NT$ into the BFSK signal

$$s_n(t) = \sum_{k=0}^{D-1} \sqrt{\frac{2E_b}{NT}} p_{NT}(t) \cos(\omega_{n,k} t),$$

where $\omega_{n,k}$ is equal to $\omega_{n,m}$ (mark) or $\omega_{n,s}$ (space) depending on the sign of $d_{n,k}$. The received signal can be written as

$$r(t) = \sum_{n=0}^{N-1} \sum_{k=0}^{D-1} \sqrt{\frac{2E_b}{NT}} p_{NT}(t-\tau_n) \cos(\omega_{n,k} t + \theta_n) + n(t),$$

where $\{\theta_n = \omega_n \tau_n\}$ are modeled as independent random uniform phase offsets. Assuming perfect carrier frequency estimation and bit synchronization for each of the N channels, an N channel non-coherent detector is used, resulting in a probability of bit error of $P_e = \frac{1}{2} e^{-\frac{E_b}{2N_o}}$.

B. Single Transmitter on a Single Channel (STSC)

In this scheme each of the N nodes transmits its D data bits to a single relay node which then transmits the entire collection of $N \cdot D$ bits to an orbiting satellite. At the relay node transmitter, the data, $\{d_0 \cdots d_{N \cdot D-1}\}$, are encoded at a rate $1/T$ into a BPSK signal. This signal is transmitted, and subsequently received at the orbiter with a path delay of τ.

Assuming perfect carrier frequency and phase estimation as well as bit synchronization, coherent reception results in a probability of bit error of $P_e = \Phi\left(-\sqrt{\frac{2E_b}{N_o}}\right)$.

For the non-coherent scheme the data is also encoded at a rate $1/T$, this time into a BFSK signal. Assuming perfect carrier frequency estimation as well as bit synchronization, non-coherent reception results in a probability of bit error of $P_e = \frac{1}{2} e^{-\frac{E_b}{2N_o}}$.

C. Multiple Transmitters on Orthogonal Channels (MTOC)

In this scheme each of the N nodes shares and orders its D data bits with each of the other nodes. Then, at the arrival of the transmission window, the nodes acquire bit synchronization with each other and each simultaneously transmits the entire ordered set of data, $\{d_0 \cdots d_{N \cdot D-1}\}$, to the orbiter on an orthogonal channel (frequency band, in our example). The n^{th} node will encode the ND data bits, $\{d_{n,0} \cdots d_{n,ND-1}\}$, at a rate $1/T$ into a BPSK signal. This signal is transmitted and subsequently received along with those of the other nodes at the orbiter, each with a separate delay of τ_n. Assuming perfect carrier frequency and phase estimation as well as bit synchronization for each of the N channels, an N channel coherent detector is used that combines received signal energies from all the channels for each bit, resulting in a probability of bit error of $P_e = \Phi\left(-\sqrt{\frac{2E_b}{N_o}}\right)$.

Similarly, for the non-coherent case the n^{th} node will encode the data bits at a rate $1/T$ into a BFSK signal. Assuming perfect carrier frequency estimation as well as bit synchronization for each of the N channels, use of an N channel non-coherent detector results in bit error probability of

$$P_e = \frac{1}{2^N} e^{-E_b/N_o} \sum_{k=1}^{N-1} \frac{1}{2^k} \binom{N+k-1}{k} {}_1F_1(N+k, N, E_b/2N_o),$$

where ${}_1F_1(\cdot)$ is the confluent hypergeometric function.

D. Multiple Transmitters on a Single Channel (MTSC)

In this scheme, all of the N nodes again share, order and bit synchronize their D data bits with each other and then simultaneously transmit the entire ordered set of data, $\{d_0 \cdots d_{N \cdot D-1}\}$, to the orbiter, each at a rate of $1/T$ on a BPSK signal. As the path delay differences are small relative to the bit time, the signals are all received with the same time offset but with different carrier phases. Assuming perfect carrier frequency and bit synchronization, single-channel coherent detection results in a probability of bit error of $P_e = \frac{1}{2}\left(1 - \sqrt{\frac{E_b/N_o}{1+E_b/N_o}}\right)$ [1].

For an equivalent non-coherent scheme the data is encoded into a BFSK signal. Assuming perfect carrier frequency and bit synchronization, non-coherent detection results in a probability of bit error of $P_e = \frac{1}{\frac{E_b}{N_o}+2}$.

E. Phase Alignment on a Single Channel (PASC)

This scheme is similar to the previous scheme in that each of the N nodes shares and orders its D data bits with each of the other nodes and, at the arrival of the transmission window, the nodes acquire bit synchronization with each other. In addition, for this scheme, the carrier phases of each node are adjusted through a feedback mechanism to arrive in phase at the orbiter. Each node then simultaneously transmits the entire ordered set of data, $\{d_0 \cdots d_{N \cdot D-1}\}$, to the orbiter. At the n^{th} node, the $N \cdot D$ data bits are encoded at a rate $1/T$ into a BPSK signal

$$s_n(t) = \sum_{k=0}^{N \cdot D-1} \sqrt{\frac{2E_b}{NT}} d_k p_T(t) \cos(\omega t + \theta_n),$$

where θ_n is the dependent carrier phase offset for the n^{th} node. This signal, simultaneously along with those of the other carrier-synchronized nodes, is transmitted to the orbiter. As the path delay differences are small relative to the bit time, the signals are all received with the same time offset, and due to the phase synchronization they are all received in-phase. Modeling the receiver front end noise as an additive Gaussian noise process, $n(t)$, with a flat power spectral density of $N_o/2$, we write the received signal as

$$r(t) = \sum_{k=0}^{N\cdot D-1} \sqrt{\frac{2E_bN}{T}} d_k p_T(t-\tau)\cos(\omega_c t) + n(t),$$

where we have arbitrarily set the common received phase to zero. Assuming perfect carrier frequency and bit synchronization, coherent detection results in a probability of bit error of $P_e = \Phi\left(-\sqrt{\frac{2NE_b}{N_o}}\right)$.

A comparable non-coherent scheme encodes the data into BFSK signals. Assuming perfect carrier frequency and bit synchronization, non-coherent detection results in a probability of bit error of $P_e = \frac{1}{2}e^{-\frac{NE_b}{2N_o}}$.

F. Node Selection on Orthogonal Channels (NSOC)

In this new cooperative modulation scheme, each of the N nodes shares and orders its D data bits with each of the other nodes. At the arrival of the transmission window the nodes acquire bit synchronization with each other. The data stream is then divided into groups of $log_2 N+1$ bits, where the first $log_2 N$ bits selects which one of the N nodes will transmit the remaining bit in that group on its orthogonal channel; this is repeated until all $N\cdot D$ bits are transmitted. This will create a bi-orthogonal signal constellation for the transmission of the $N\cdot D$ bits to the satellite; information is conveyed in the transmitted bit as well as on which channel the bit is received. For example, consider the case where each node is assigned a unique frequency band. The n^{th} node, when selected to transmit, will encode a data bit, d_k, into a BPSK signal

$$s_n(t) = \sqrt{\frac{2E_b}{(\log_2 N+1)T}} d_k p_{T'}(t)\cos(\omega_n t),$$

where E_b is the received energy-per-bit and $p_{T'}(t)$ is a rectangular pulse of duration $T' = (\log_2 N+1)T$. Only this signal from the one selected node is transmitted and subsequently received at the orbiter with a delay of τ_n. We model the receiver front end noise as an additive Gaussian noise process, $n(t)$, with a flat power spectral density of $N_o/2$, and write the received signal as

$$r(t) = \sqrt{\frac{2E_b}{(\log_2 N+1)T}} d_k p_{T'}(t-\tau)\cos(\omega_n t+\theta_n) + n(t),$$

where $\theta_n = \omega_n\tau_n$ is modeled as an independent random phase offset. Assuming perfect carrier frequency and phase estimation as well as bit synchronization for each of the N channels, the N channel coherent detector shown in Figure 1 is used, resulting in a probability of bit error of

$$P_e = \frac{1}{2}\left[1 + \int_{-\infty}^{-\sqrt{ME_b/N_o}} \frac{e^{-x^2}}{\sqrt{\pi}}\left[\operatorname{erfc}(x+\sqrt{ME_b/N_o}) - 1\right]^{N-1} dx\right.$$

$$\left. - \int_{-\sqrt{ME_b/N_o}}^{\infty} \frac{e^{-x^2}}{\sqrt{\pi}}\left[1 - \operatorname{erfc}(x+\sqrt{ME_b/N_o})\right]^{N-1} dx\right],$$

where $M = \log_2 N + 1$ [2].

When using a non-coherent modulation, as in the case of orthogonal frequencies and BFSK modulation, this will create an MFSK signal constellation (with $M = 2N$) for the transmission of the $N\cdot D$ bits to the satellite; again the information is conveyed in the transmitted bit as well as on which channel the bit is received. Using our standard example in which each node is assigned a unique frequency band and BFSK modulation is used, a non-coherent version of the detector shown in Figure 1 would yield bit error probability

$$P_e = \frac{2N}{2(2N-1)} \sum_{n=1}^{2N-1} (-1)^{n+1} \frac{1}{n+1}\binom{2N-1}{n} \times \exp\left(-\frac{n}{n+1}(\log_2 N+1)E_b/N_o\right).$$

Plots of the probability of bit error versus E_b/N_o for the coherent scheme only shown in Figure 2.

III. Local Communications

All of the cooperative modulation methods require that information be shared locally before long haul transmission. In order to compare these schemes to each other and to the non-cooperative scheme, the amount of energy expended in this local communication must be accounted for. Therefore, methods of information dissemination among the sensor nodes must be determined along with the type of link best suited to that task for a particular cooperative method [3]. A local cost in terms of energy-per-shared-bit can then be determined for these under various network topologies. By associating this cost with a particular cooperative modulation method, a local communication penalty in terms of the overall energy-per-bit may be assessed. This allows comparisons of these schemes with each other as well as with the non-cooperative scheme.

A. Methods for Information Dissemination

Two methods of disseminating information among the nodes of a local area network have been considered: aggregation and gossiping. The aggregation problem is defined as the delivery of data from all nodes to a particular node. This corresponds to the cooperative case of the single transmitter single channel in which all the data in the network are sent to a single long-haul radio for transmission. In the gossiping problem each node has a message of length D which must be shared with all of the other N nodes. This method describes the the necessary information dissemination for all the other cooperative cases except the node-selection orthogonal channels where it can be used as upper bound on the number of transmissions required for information dissemination.

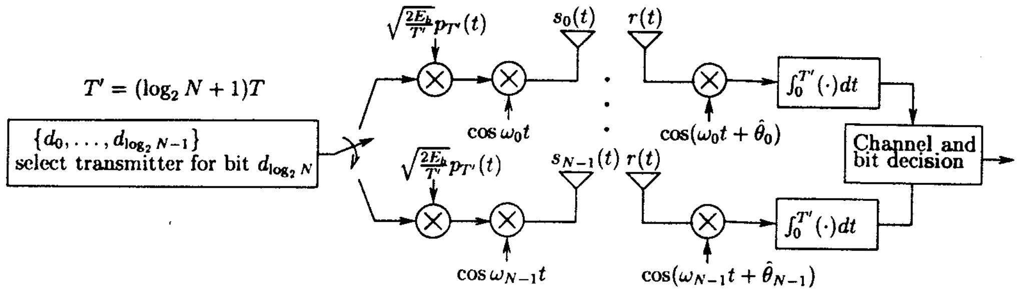

Fig. 1. Node-selection orthogonal transmission scheme with BPSK modulation.

B. Link Type

The local network communications can be implemented with two types of links: point-to-point and multi-cast. In a point-to-point link messages are exchanged between a transmitter and receiver pair, whereas in a multi-cast link there may be multiple receivers of the message sent from a single transmitter. The expense of an increased number of received bits is offset by the reduced number of necessary transmissions and, in general, information can be transmitted more efficiently using multi-cast links.

As we are concentrating on the gross energy expense we assume that the links are half-duplex and that the underlying protocol supports variable length packets so that information can be concatenated to a message. We will not consider the time to switch between transmitter and receiver. Contention for the medium and simultaneous transmission interference effects will also not be considered. Furthermore, the nodes are assumed to be capable of store-and-forward operation so that a message will pass through one or more intermediate nodes if the source and destination nodes are not directly connected. The number of intermediate nodes plus the final destination is referred to as the number of hops for the message. Topologies with multi-hop routes will require multiple transmissions of a message as it is passed through the network.

C. Topologies

Several regular topologies will be considered in order to provide estimates of the energy use of local communications. These types of graphs are useful for comparisons but are not expected to occur in actual networks that may be randomly deployed or arranged to cover a particular physical area.

The following topologies are considered: (1) A linear topology of N nodes ($N-1$ hops), where each node is separated by an equal distance, and (2) A complete $\sqrt{N} \times \sqrt{N}$ grid of N nodes covering a square grid where each interior node is connected to 4 other nodes, an edge node is connected to 3 nodes, and a corner node is connected to 2 nodes.

D. Local Communication Costs

In order to obtain the energy required to disseminate the information, the total amount of energy spent transmitting on each hop must be estimated. This depends on the topology, the type of link (point-to-point or multi-cast), the distance per hop, and the transmit power. For now, we are not considering the overhead necessary to establish or maintain the network (additional bits used for header information, check sums); in essence, we are assuming that there are no costs in providing contention-free medium access. In the multi-hop networks, this means we are also not considering the costs of determining the routes, the internal computations or buffering.

Under these assumptions, the energy cost becomes solely a function of the path distances. For example, in order to achieve the same performance on each hop of a multi-hop network, the received energy-per-bit, E_b, at each hop must be equal. This requires a transmit energy-per-bit-per-hop of $E_b r^\gamma$, where r is the distance between nodes and γ is the path loss exponent. In free space γ is equal to 2; however for ground communications it typically resides between 3 and 5 depending on factors such as the terrain, frequency, and antenna heights. The total energy expended in 'hopping' a bit across h nodes is, therefore, $E_t = E_b \cdot h \cdot r^\gamma$.

For each of the two topologies the energy-per-bit costs under each of the information dissemination classes (aggregation, gossip) can be determined under both link types (point-to-point, multi-cast); the number of local transmissions per bit, M, are summarized in Table I.

IV. Comparison

The bit error performances of the cooperative modulation schemes are compared with each other and the non-cooperative scheme in Figs. 3 and 4. In all of these comparisons, the energy cost of the local communication necessary to share the information prior to long-haul transmission via a particular cooperative modulation method has been approximated using the number of local transmissions per bit necessary to support that scheme. This local energy cost per bit has been approximated by assuming that the communication method used on the local link is the same as that of the particular cooperative scheme being considered. As the energy expended in local communications would be unavailable to the long haul transmission we incorporate these costs into the performance of each scheme by subtracting from received energy-per-bit, E_b, an amount equal to the relative local communications energy-per-bit cost, $E_b \cdot M \cdot r_1^3/r_2^2$.

As an example scenario consider a system with N nodes layed out in a complete grid with a node separation of $r_1 = 1.5km$. The long haul link is with an orbiting satellite at $400km$, and all local communication links are multi-cast. Fig. 3 contains a plot of the probability of bit error versus the number of nodes N for the coherent schemes with an E_b/N_o of 10 dB. The performance of the non-cooperative scheme (NCOC) is fixed while that of the single transmitter on a single channel (STSC) and the multiple transmitters on orthogonal channels (MTOC) decreases. This is due to the increase in local communications costs as the number of nodes increases. While there are clear reasons one might use the STSC scheme (simplicity of the receiver, availability of a single high power transmitter), there is little reason to use the MTOC scheme over the non-cooperative scheme given the added energy cost of sharing the information locally. The multiple transmitters on a single channel (MTSC) scheme has the poorest performance of the cooperative schemes with a probability of bit error that exceeds the non-cooperative scheme and decreases only inversely proportional to the energy-per-bit. Both the phase-aligned on a single channel (PASC) and node-selection on orthogonal channels (NSOC) schemes offer significant energy savings over the non-cooperative scheme. For the NSOC method the local communication costs come to dominate as the number of nodes increase resulting in a performance cross over with the non cooperative method. This is due to the diminishing gains of a bi-orthogonal modulation as the number of dimensions increases. The PASC scheme allows the use of a single channel receiver, as compared to the multi-channel receiver used in the non-cooperative scheme; however the feedback mechanism will place an additional complexity burden on the transmitters. The NSOC method, on the other hand, places the complexity burden on the receiver, requiring the multi-channel receiver used in the non-cooperative scheme. Fig. 4 contains a similar plot for the non-coherent schemes.

V. Conclusion

The use of cooperative modulation techniques in reducing the energy requirements for the long-haul relay of data from localized sensor networks was examined. Several different schemes were presented and the performance of each was analyzed. The local communication costs necessary to support these different cooperative modulation schemes were determined and incorporated into a comparison of their performances. Two of the schemes showed significant energy savings over the non-cooperative scheme demonstrating the energy savings that can be obtained by using a cooperative modulation technique.

References

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[3] Mischa Schwartz, *Telecommunication Networks*, Addison Wesley, Reading, MA, 1987.

Topology	Dissem.	Link Type	
		pnt-to-pnt	multi-cast
Linear	gossip	$N-1$	$N-2+2/N$
	aggregation	$(N-1)/2$	$(N-1)/2$
Complete Grid	gossip	N-1	$N/2+3\sqrt{N}/2-2$
	aggregation	$\sqrt{N}-1$	$\sqrt{N}-1$

TABLE I

Number of transmissions-per-bit for local communications.

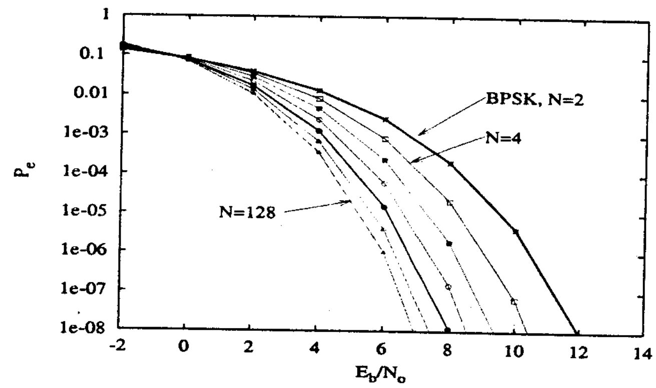

Fig. 2. Bit error probabilities for node-selection orthogonal transmission scheme with BPSK modulation.

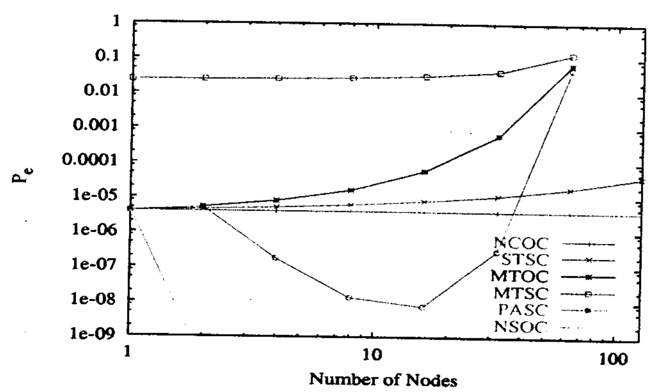

Fig. 3. Comparison of P_e versus number of nodes for various coherent BPSK transmission schemes at an E_b/N_o of 10 dB.

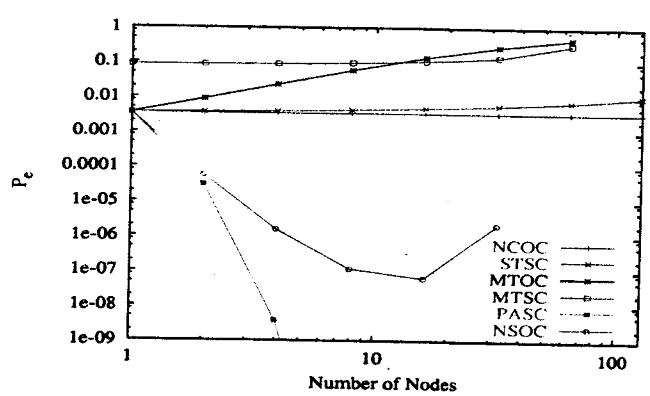

Fig. 4. Comparison of P_e versus number of nodes for various non-coherent BFSK transmission schemes at an E_b/N_o of 10 dB.